Reclassification of the Piracicaba Tornado (January 31, 2025): Retrospective Analysis of the Track Based on Meteorological, Botanical, Geological Evidence and Physical Modelling

Erik K. dos Santos

St. Marys District Collegiate and Vocational Institute

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Author Note

Erik dos Santos is a supervisor at Piracicaba Meteorológica (Meteorological Piracicaba) and was temporarily affiliated with the St. Marys District Collegiate and Vocational Institute.

This research was initially developed within the scope of Piracicaba Meteorológica as part of an ongoing institutional investigation regarding the tornado event of January 31, 2025. Following the relocation of the primary research infrastructure from Piracicaba, Brazil, to St. Marys, Ontario, Canada, in May 2026, the final diagnostic review and intensity classification methodology were concluded at the St. Marys District Collegiate and Vocational Institute, where the study was officially submitted to the Science Department and accepted by the Institution's Management Team. This final publication is issued and maintained by Piracicaba Meteorológica.

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Correspondence concerning this article should be addressed to Erik Kaue dos Santos. Email: erikkaue4256@gmail.com or erikdoss889@ed.amdsb.ca

Abstract

This study analyzes the tornado that occurred in Piracicaba, in southeastern Brazil, on January 31, 2025. The initial investigation integrated satellite data, weather radar, surface records, amateur footage of the phenomenon, and three-dimensional modeling of the associated storm. In an additional phase conducted between February and May 2026, a retrospective forensic analysis of the tornado's possible path was performed using remote sensing, street images, and morphological assessment of vegetation damage. This investigation identified structural rupture of large branches, permanent twisting of trunks, and extensive damage to a eucalyptus plantation along the previously estimated path of the phenomenon on the Jacob Canale Municipal Road, in the Campestre neighborhood. Based on this evidence, the event is reclassified in this study as an EF1 tornado on the Enhanced Fujita Scale.

Keywords: Tornado, supercell, severe weather

Reclassification of the Piracicaba Tornado (January 31, 2025): Retrospective Analysis of the Track Based on Meteorological, Botanical, Geological Evidence and Physical Modelling

Tornadoes constitute high-intensity meteorological phenomena, defined as violently rotating columns of air extending from the base of a convective cloud to the ground surface (Doswell & Burgess, 1993). Frequently associated with severe storms and, particularly, supercells, these systems exhibit a complex vertical structure characterized by intense updrafts, vertical wind shear, and high atmospheric instability (Markowski & Richardson, 2010). According to Wollmann and Iensse (2019), the occurrence of tornadoes in southern and center-southern Brazil is not considered rare and represents one of the atmospheric events with the greatest destructive potential, capable of causing significant damage to urban, agricultural, and critical infrastructure areas, in addition to substantial socioeconomic impacts (Lima & Selani, 2008; Lopes & Nascimento, 2025).

Within the South American context, the existence of the so-called South American Tornado Corridor stands out, extending primarily through northern Argentina, Uruguay, Paraguay, and southern and center-southern Brazil (Lopes & Nascimento, 2025; Wollmann & Iensse, 2019; Zipser et al., 2006). Piracicaba, located in the interior of the state of São Paulo, is susceptible to the formation of severe storms due to its location within this corridor. The tornado recorded between 22:04 and 22:06 UTC on January 31, 2025, in Piracicaba garnered special attention from the local meteorological community, demanding an integrative analysis to consolidate the understanding of this phenomenon.

Literature Review

Among the favorable factors for the genesis of supercells and tornadoes in the Piracicaba region, the prominent elements are the convergence between air masses with distinct characteristics, the presence of troughs in the mid-levels of the troposphere, and the interaction between jet streams at different altitudes, which intensify vertical wind shear and mesocyclonic rotation (Doswell & Burgess, 1993; Markowski & Richardson, 2010; Wollmann & Iensse, 2019). When combined, these elements create a conducive environment for the development of deep convection and the organization of mesoscale convective systems.

Previous Investigations: The February 2025 Study

The first scientific work dedicated to the tornado recorded in Piracicaba was published on February 23, 2025, by Santos (2025b). The primary objective was to examine the event using publicly accessible records, including amateur video footage, meteorological stations, and satellite data. However, the study exhibited structural and methodological weaknesses, with organizational issues and a narrative style that conveyed textual ambiguity regarding the confirmation of the tornado's occurrence. Analytically, the investigation was limited to describing the convergence of surface winds from the west and east, failing to provide a broader synoptic contextualization (such as the influence of troughs or jet streams), which weakened the initial identification of the touchdown point in the Jardim Belvedere subdivision.

Previous Investigations: The May 2025 Revision

Published on May 2, 2025, by Santos (2025a), the second study represented a georeferenced review of the initial analysis using Google Earth Pro software. By identifying fixed geographic reference points within the amateur video footage, the horizontal trajectory was estimated, and the contact point with the ground was repositioned to a vegetated area near the

Ribeirão do Enxofre stream in the Jardim Santa Fé subdivision. The May study discussed and dismissed the hypotheses of multiple vortices and waterspouts. In terms of intensity, the absence of severe structural damage or significant defoliation corroborated the classification of the tornado as an F0 on the original Fujita Scale, with winds estimated below 100 km/h and a trajectory of approximately 50 to 150 meters.

Method

Data Sources and Meteorological Reanalysis

The synoptic and mesoscale analysis was structured around the observation of atmospheric behavior during the period of the event. As an initial reference, the forecast report document provided by the Weather Research Forecast (WRF) model of the Brazilian Reporting Platform of Severe Weather (PRETS) (Ribeiro et al., 2022) was utilized, which delivered Convective Available Potential Energy (CAPE) estimates, as well as information on relevant synoptic and mesoscale factors. To ensure consistency, public data provided by the Center for Weather Forecasting and Climate Studies (CPTEC) of the Brazilian National Institute for Space Research (INPE) were incorporated, enabling the analysis of wind fields at different levels of the troposphere, the identification of low-level convergence patterns (interaction between westerly and easterly winds), and the evaluation of the South Atlantic Convergence Zone (SACZ) configuration.

Radar and Satellite Assessments

The characterization of the convective cells associated with the event was performed through the integration of observational and remote sensing data from CPTEC/INPE and the IPMet/UNESP meteorological radar. Satellite imagery provided estimates of the cloud-top

temperature of the convective systems, a parameter used to infer cloud-top altitude based on the classic mathematical relationship:

$$h = \frac{T_{ground} - T_{top}}{T}$$

where T_{ground} corresponds to the surface temperature, T_{top} to the cloud-top temperature, and T to the average vertical thermal gradient of the troposphere (adopting 6.5 °C/km). Additionally, radar data allowed for the tracking of the horizontal movement of the cells and the measurement of their spatial organization, complemented by surface temperature and humidity records obtained from the Integrated Center for Agrometeorological Information (CIIAGRO).

Three-Dimensional Modelling and Path Verification

Three-dimensional modeling of the tornado and its trajectory was conducted using Google Earth Pro software, spatially reconstructing the tornado funnel, the wall cloud, the precipitation region, and the base of the convective cell. The altitude of the cell base was estimated by calculating the LCL (*Lifted Condensation Level*), obtained through Espy's equation:

$$LCL = 125\ (T - Td)$$

where T corresponds to the air temperature (°C) and Td to the dew point temperature (°C) recorded at local surface stations. This geometric modeling refined the trajectory parameters derived exclusively from the video record.

Kinematic Profile Compensation and Boundary-Layer Scalling

To resolve the non-physical stagnation identified in the lower troposphere within the raw reanalysis fields, a physically constrained kinematic profile compensation was applied to the vertical wind structure up to the mid-tropospheric steering level (500 hPa). This correction framework reconciles sub-grid scale friction damping with the observed storm translation and regional synoptic forcing through a two-tiered vertical scaling approach. Within the planetary

boundary layer (PBL), the vertical distribution of horizontal wind velocity was parameterized using a standard power-law wind profile to smooth sub-grid scale surface friction and accurately project momentum transport:

$$U(z) = U_{ref} \cdot \left(\frac{z}{Z_{ref}}\right)^{\alpha}$$

where *U(z)* represents the estimated wind velocity at height *z*, U_{ref} is the baseline velocity recorded at the reference surface station layer (Z_{ref}), and α is the dimensionless wind profile exponent (adopting 0.20) to represent the characteristic surface roughness and frictional drag of the regional mixed terrain during convective instability. Above the boundary layer (850 hPa), the transition toward the synoptic-scale circulation driven by the 500 hPa stationary trough was parameterized through a linear–logarithmic vertical momentum compensation, constrained by the maximum 15 m/s wind speed vector provided by the PRETS' WRF regional operational model and the 27 m/s wind speed vector registered at 850 hPa by CPTEC, adjusted for localized mesoscale boundary layer currents and storm-scale gust front advection.

Retroactive Botanical Thorough Procedures

A second investigative phase was conducted retroactively between February and June 2026 to identify physical evidence of vegetation damage along the estimated tornado corridor.

Remote sensing and imagery analysis. The investigation began with a multi-temporal analysis of high-resolution orbital imagery from the Landsat (NASA), Pléiades Neo (Airbus), and Maxar Technologies programs to detect medium-term alterations in the forest canopy and vegetative structure within the impact area.

Biomechanical evaluation. The analysis of this damage was based on the interpretation of the biomechanical characteristics of the wood and typical structural failure patterns resulting

from severe wind action, distinguishing between failures caused by bending, shear, and torsion. Parameters considered included the dimensions of the fractured elements, the spatial orientation of the fallen branches and trunks, and the level of aging in the exposed wood (drying cracks and lignin photodegradation from UV radiation) to verify the precise timing of the event.

Intensity estimation and metric adjustment. To estimate wind speed, the observed damage was empirically compared with dozens of historical records of structural tree failure during severe wind events in the region between 2005 and 2025, and adjusted to the mechanical resistance of the identified species. Due to the physical relocation of the research equipment to the town of St. Marys (Ontario, Canada) in April 2026, the vegetation damage classification methodology was updated to formally integrate the current degrees of damage (DODs) of Enhanced Fujita (EF) Scale from both Texas Tech University (2006) and Environment Canada (2013) methodologies.

Results

The first phase of the tornado analysis was conducted between September and October 2025. The investigation utilized amateur video footage, meteorological radar data, and three-dimensional geometric reconstruction to refine previous preliminary estimates (Santos, 2025a, 2025b). Initial integration of these data sources placed the touchdown point within an agricultural zone in the rural district of Pau Queimado, Piracicaba, São Paulo. This initial assessment indicated that the vortex remained confined to sugarcane fields, contrasting with earlier hypotheses that situated the event in the unpopulated areas of the Campestre neighborhood.

Three-dimensional modeling was executed via Google Earth Pro by aligning fixed geographic references visible in the footage, including telecommunication towers, rural structures, and topographic features. The vortex core diameter was estimated at approximately 40 meters at the surface, with a visible funnel height of approximately 200 meters. The associated wall cloud diameter was measured at around 1 kilometer. The analysis of the footage further suggested that the funnel maintained intermittent surface contact, with an initial estimated horizontal extension of 175±25 meters. The apparent displacement vector of the vortex indicated a translation velocity between 7 and 8 km/h, calculated from a 200-meter displacement over a 2-minute interval between 22:04 and 22:06 UTC, moving predominantly toward the southeast. In February 2026, a multi-temporal satellite imagery analysis identified a sutil linear anomaly in a sugarcane crop near the Jacob Canale Municipal Road. Because this irregularity aligned with the estimated translation vector, a specialized forensic stage was initiated to investigate physical evidence of wind damage in the adjacent vegetation.

In February 2026, a multi-temporal satellite imagery analysis identified a subtle linear anomaly in a sugarcane crop near the Jacob Canale Municipal Road. Because this irregularity aligned with the estimated translation vector, a specialized forensic stage was initiated to investigate physical evidence of wind damage in the adjacent vegetation. Following the retroactive botanical forensic analysis of the damage track in March 2026, the spatial delimitation of the touchdown point was significantly refined. While the initial photogrammetric estimate derived exclusively from the video footage placed the initial ground contact at approximately 22°46'19"S and 47°41'49"W, the integration of physical evidence from the vegetative field survey allowed for the repositioning of the track start to approximately

22°45'50.5"S and 47°41'19.2"W, locating the initial touchdown politically within the Campestre neighborhood, along a territorial transition zone with the Pau Queimado district.

Empirical Reconstruction of the Tornado Track via Botanical Evidence

The second phase of the study, carried out between February and March 2026, sought direct biophysical evidence to validate the track parameters. Initial multi-temporal analysis of Landsat imagery confirmed a narrow, linear swath of slightly reduced vegetative vigor near the Jacob Canale Road, which prompted a high-resolution inspection of street-level imagery from June 2025.

Within a roadside tree cluster composed primarily of *Leucaena leucocephala*, a large primary branch with a length of approximately 2.5 meters and a basal diameter of approximately 25 centimeters was found fractured and displaced at approximately 4 meters above the ground. While initial aging and exposure calculations suggested the failure occurred between November 2024 and February 2025, a subsequent diagnostic review conducted in St. Marys, Ontario, Canada, in May 2026 overturned this hypothesis. Detailed structural analysis revealed advanced internal heart rot, indicating the branch had been down for years, likely prior to the 2024–2025 rainy season or during the 2023 calendar year. Furthermore, extensive evidence of anthropogenic clearing and excavation rendered this specific specimen invalid as a tornado indicator. On the opposite side of the road, a young eucalyptus of approximately 2 meters in height exhibited a permanent trunk torsion with a 20° northward inclination, denoting lateral shear stress beyond the proportional elastic limit of the wood, while further west, a desiccated tree displayed a 30° northward tilt alongside a partial fracture of the upper canopy.

A commercial eucalyptus plantation on the southwest margin of the Jacob Canale Municipal Road displayed extensive convective wind damage (Figure 1). Street-level images from June 2025 revealed a distinct, linear West-to-East damage swath characterized by severe canopy defoliation, structural trunk deformations, lodging, and complete main stem fractures. Multi-temporal Landsat data confirmed the site had undergone replanting in 2023, suggesting a pre-existing structural vulnerability in the younger arboreal mass. Nonetheless, the coexistence of extensive aerodynamic defoliation, intense vertical axis torsion, and clean stem fractures indicates aerodynamic loads exceeding standard F0 thresholds, implying a localized wind field intensity significantly higher than initially estimated.

Figure 1

Snapping and growth stress in eucalyptus plantation along the Jacob Canale Road (Campestre)

Note: Adapted from Google Street View (Google, 2025a)

An isolated eucalyptus specimen along the central axis of the track exhibited a damage pattern distinct from the drought-stressed arboreal mass (Figure 2). The specimen lacked biological degradation, fungal rot, or root compromise, indicating full vegetative vigor at the time of impact. The damage consisted of top-out canopy removal accompanied by extensive trunk debarking, and at least four adjacent eucalyptus trees displayed identical linear debarking patterns. Trunk debarking in healthy, high-growth structural timber requires high dynamic pressure to overcome the adhesive moisture bond between the bark and the inner xylem. This specific failure mode aligns directly with the tree-damage indicators (DI 27, Degrees of Damage 3 and 4) for small-trunk hardwood or commercial timber trees under the United States Enhanced Fujita Scale framework, corresponding to the EF2 intensity threshold (Texas Tech University, 2006). Rather than reverting to regional adaptations or traditional conversion metrics, the analysis maintained adherence to the standardized operational protocols of the United States and Canada framework to evaluate the aerodynamic load required to overcome the adhesive moisture bond between the bark and the inner xylem. However, due to the spatial discontinuity of the damage path, this EF2 rating cannot be definitively generalized to the entire path length.

Figure 2

Decapped eucalyptus tree between the newly constructed roads and the Jacob Canale Road (Campestre)

Note: Adapted from Google Street View (Google, 2025b)

Integrating the verified botanical vectors allowed for a more precise cartographic delimitation of the tornado track. According to the field survey compiled on March 20, 2026, as shown in Figure 3, the total distance between the outermost confirmed damage points reached approximately 300 meters along a West-Northwest to East-Southeast axis. This distance significantly expands the initial estimate of 175±25 meters derived from the photogrammetric analysis. The cross-sectional distribution of damaged trees indicates a maximum path width

between 50 and 80 meters, slightly exceeding the visual funnel width of approximately 40 meters. Furthermore, considering this 300-meter track and the reported duration of 1 to 2 minutes, the tornado moved at an estimated translation speed ranging from 9 to 18 km/h.

Figure 3

Preliminary track delimited on March 20, 2026 (in Portuguese)

200 m
Estrada Municipal Jacob Canale
TRAJETÓRIA PRELIMINAR DO TORNADO DE 31 DE JANEIRO DE 2025 EM PIRACICABA/SP
Delimitação prévia de 20 de março de 2026
Trajetória (núcleo)
Corredor intermitente de danos (estimado)
Áreas arbóreas
Solo exposto / áreas agrícolas
Malha viária
Produto em construção, elaborado para fins acadêmicos.
Base derivada de imagem de satélite convertida para cartografia por IA (GPT-5).
Delimitação preliminar e sujeita a revisão.
FONTES:
Satélite LandSat 9 (NASA)
Licença Creative Commons – CC BY 4.0 (atribuição obrigatória)
PIRACICABA
METEOROLÓGICA
Desde 2023

Note: From the Piracicaba Meteorológica archives.

On March 22, 2026, an attempt was made to expand the track limits by assessing herbaceous vegetation using enhanced-resolution Google Street View samples from June 2025,

comparing them against ground conditions near a recently constructed road network to the north, where four areas of lodged, dry grass were identified and designated as A1, A2, A3, and A4. Zones A2 and A4 were immediately excluded due to clear signs of mechanical weeding, while zone A3 exhibited topographic grading with heavy anthropogenic disturbance. Zone A1, although aligned with the track axis, sat upon soil highly depleted of organic matter, and Maxar Technologies imagery from 2020 confirmed that this northern zone underwent deep excavation during road construction, exposing lithic subsoil layers and inducing severe edaphic stress, which accelerated surface erosion. Street View records from September 2022 showed ongoing excavations and brush fires, giving the surface a semi-arid, Caatinga-like appearance, even though the regional soil profile is classified as an Argisol-Latosol transition (Teramoto et al., 2001). Consequently, the herbaceous indicators lacked diagnostic reliability and were excluded from the final track definition.

Multi-temporal analysis using Airbus Pléiades Neo 3 and 4 satellite imagery identified structural changes in a livestock pen located approximately 470 meters northwest of the eucalyptus plantation. Comparison between late 2024 and early 2025 scenes revealed irregular, high-albedo linear features over the roofed area, consistent with shattered asbestos-cement tiles. Street-level verification from June 2025 confirmed scattered fragments of asbestos-cement roofing and zinc sheets within the perimeter, where a portion of the debris was concentrated in a neat pile, while the remaining fragments showed restricted dispersion with no coherent directional alignment. The perimeter fencing showed no signs of structural failure. This debris pattern contradicts the typical signatures of weak tornadic winds, which distribute low-mass materials in a highly directional, divergent pattern. Furthermore, the structure sits approximately 350 meters outside the three-dimensional georeferenced track model established by Santos

(2025a), completely lacking spatial continuity with the documented botanical damage path. Therefore, alternative non-tornadic causes are highly probable, such as independent convective downbursts during the same season, progressive degradation from standard non-severe windstorms, illegal rural dumping, or a lack of structural roof maintenance. This site was excluded from the final intensity and track calculations.

Synoptic and Mesoscale Profile

Atmospheric reanalysis identified the presence of environmental ingredients favorable for marginal supercellular convection. At mid-levels, a stationary trough at 500 hPa interacted with a Mean-Layer CAPE of 1000±500 J/kg and a vertical wind shear of 12.5±2.5 m/s, sustaining a moderately unstable thermodynamic environment. The convection was further amplified by low-level moisture convergence along a boundary separating warm, dry continental air from the state's interior and cool, maritime air from the Atlantic, with the South Atlantic Convergence Zone providing steady moisture advection.

The convective cell exhibited classical supercellular features, maintaining an isolated structure during its core life cycle. The storm-top altitude reached approximately 13.1 kilometers, calculated from the thermal differential between the surface at approximately 25°C and the cloud-top infrared temperature at approximately -60°C obtained from satellite imagery. The Lifted Condensation Level, representing the cloud base, was established at approximately 500 meters using Espy's equation. The cell initiated at approximately 21:10 UTC in the central rural sector of the municipality and subsequently merged into a larger mesoscale convective complex that had been expanding since 19:00 UTC. Satellite data confirmed sustained cloud-top temperatures below -60°C until 23:20 UTC.

Photogrammetric analysis of the available video footage further revealed that the core tornadic funnel was enveloped by multiple persistent, high-contrast scud clouds exhibiting regular contours beneath the storm base, as shown in Figure 4. Instrumental observations obtained from local networks registered only a multicell convective system without automated mesocyclone signatures. This scaling limitation is evidenced by operational satellite imagery from CPTEC, which tracked cloud-drift transits at velocities exceeding 50 km/h (13.9 m/s). This empirical observation shows a discrepancy in the raw reanalysis data, where the uncompensated profile indicates an extremely stagnant lower troposphere, with velocities dropping to 15.2 km/h at 500 hPa, that is physically incompatible with the observed storm momentum. Therefore, a physically constrained, kinematic profile compensation was required to accurately evaluate whether resolved boundary-layer processes could support the documented tornadogenesis.

Figure 4

Visual structure of the core tornadic funnel and peripheral cloud condensation

Note: From the Piracicaba Meteorológica archives, digitally enhanced to high definition (HD).

The low-level wind fields extracted from numerical models showed velocities under 2 m/s between the surface and 850 hPa, which probably underestimated the regional synoptic momentum transport. To resolve this, a dynamic profile compensation was applied using a standard power-law wind profile exponent ($\alpha = 0.2$) for the planetary boundary layer (until 850 hPa), smoothing the sub-grid scale friction and aligning the lower troposphere with the mid-level trough forcing. Above 850 hPa, wind velocities were parameterized through a linear–logarithmic vertical momentum shear scaling framework, providing a physically consistent transition between the boundary-layer regime and the free-tropospheric synoptic circulation.

It is critical to emphasize that the adjusted data presented in Table 2 does not constitute an arbitrary empirical correction. Rather, it represents the minimum physically plausible kinematic profile required to support and sustain a deep convective structure with a 13 km cloud top, derived strictly from established mathematical equations and historical meteorological analogs of similar convective environments. These parameterized values are not intended to be exact measurements, nor do they substitute real observations, they serve an interpretive, diagnostic purpose to explain the precise mechanical impacts of these unmodeled dynamics on marginal storm formation.

The methodology was constrained by the 15 m/s wind speed indicated by the PRETS' model at 500 hPa and included calibrated attenuation factors to minimize the risk of overestimation while preserving the realism of the resulting vertical wind profile. Based on the adjusted profile, the 0–3 km bulk shear was calculated at approximately 12 m/s, with storm-relative helicity values of 90–120 m^2/s^2 in the 0–1 km layer and 160–210 m^2/s^2 in the 0–3 km layer, supported by an ambient upper-level outflow of 15 m/s at 500 hPa. Vertical wind profile data capturing the atmospheric state at 22:00 UTC on January 31, 2025, are presented below,

where Table 1 details the raw uncompensated data fields and Table 2 outlines the compensated operational values adjusted for localized mesoscale dynamics.

Table 1

Vertical Wind Profile at 22:00 UTC on January 31, 2025 (Raw CPTEC Data)

Level	**Velocity (km/h, m/s)**	**Direction (approximate °)**
Surface	6.5 (1.8)	ESE (110)
1000 hPa	4.5 (1.3)	NNW (330)
850 hPa	2.0 (0.5)	Clockwise rotation, slight SW bias
700 hPa	19.3 (5.4)	NW (315)
500 hPa	15.2 (4.2)	WSW (245)
250 hPa	54.5 (15.1)	NW (320)
10 hPa	96.7 (26.9)	E (80)

Table 2

Vertical Wind Profile at 22:00 UTC on January 31, 2025 (Simulated Operational Values)

Level	**Velocity (km/h, m/s)**	**Direction (approximate °)**
Surface	6.5 (1.8)	ESE (110)
1000 hPa	11.2 (3.1)	NNW (330)
850 hPa	19.3 (5.4)	SE (135)
700 hPa	36 (10)	NW (315)
500 hPa	54 (15)	WSW (245)
250 hPa	65 (18)	NW (320)
10 hPa	97 (27)	E (80)

Discussion

The localized convective environment of the January 2025 event demonstrates that tornadogenesis can occur within synoptically marginal frameworks that deviate from classical deep-convection paradigms. The regional tropospheric profile lacked the high-tier thermodynamic instability and deep vertical shear typically associated with large-scale, classic, or high-precipitation supercells (Doswell & Burgess, 1993). Instead, tornadic organization relied on the non-linear interaction of mesoscale forcing mechanisms. The primary driver was the inland penetration of the sea-breeze front, which acted as a localized source of baroclinic vorticity and mass convergence upon intersecting the regional pressure trough. This interaction generated concentrated horizontal vorticity within the boundary layer, which was subsequently tilted and stretched vertically by the storm's updraft (Markowski & Richardson, 2010).

Despite the constrained horizontal scale of the parent cell, the depth of its vertical development was sufficient to breach upper-tropospheric levels, indicating strong, localized updraft acceleration. This process was dynamically favored by an exceptionally low cloud base. Low lifted condensation levels (LCLs) reduce the vertical distance between a mid-level mesocyclone and the surface, lessening the detrimental effects of sub-cloud evaporation and accelerating low-level tornadic rotation through vortex stretching (Thompson et al., 2003). This mechanism explains how a horizontally compact storm can achieve sufficient internal organization to produce a surface-contacting vortex without relying on extreme macroscale synoptic setups.

The visual attributes of marginal convective supercell introduced significant ambiguity into initial observational assessments. The high-humidity environment underneath the cloud base

generated numerous persistent scud clouds within the turbulent inflow region. In severe weather literature, these non-rotational condensation fragments are frequently misidentified as independent vortices or tornadoes (Markowski & Richardson, 2010). In this case, the regular contours and temporal persistence of the surrounding scud cloud canopy partially obscured the core tornadic funnel, leading early peer reviews to dismiss the event as non-tornadic turbulent condensation.

Extant literature establishes that tornado genesis stems from a localized, extreme low-pressure anomaly that perturbs cyclostrophic balance (Davies-Jones et al., 2001; Smith & Leslie, 1979). In this specific event, centripetal acceleration inward cavity-directed forces drew a substantial portion of the peripheral condensation into the core, thereby inducing a characteristically wider morphology. Furthermore, the system's structural persistence and high contrast demonstrate that these formations were distinct from ordinary scud clouds, which typically exhibit a far more chaotic appearance relative to the ambient environment (Branick, 1996). Additionally, the peripheral cloud structures reflect intense inflow saturation rather than multiple independent vortices.

A critical retrospective adjustment involves the physical repositioning of the initial touchdown point. The geographical divergence between early visual models and retroactive field evidence highlights the limitations of relying solely on amateur videography for track delineation. Furthermore, the total absence of ground scars or visible paths in the initial satellite surveys caused early investigators to conclude that no tornado had occurred. However, this absence of evidence is explained by the flexible nature of the monoculture crop dominating the initial site. Flexible stalk vegetation, such as sugarcane, undergoes temporary elastic deformation under short-duration winds rather than permanent mechanical failure. Consequently, it fails to

leave long-term scars detectable by medium-resolution orbital sensors, a limitation well-documented in agricultural storm forensics (Gliksman et al., 2023; Mostafiz et al., 2022). The lack of initial crop damage was a function of vegetation mechanics at the first assumed site, which was completely refuted once physical, permanent structural damage was discovered in arboreal masses at a separate location.

The reanalysis of the mesoscale environment highlights a recurring problem regarding the underestimation of low-level wind speeds by coarse numerical forecasting products. Raw operational profiles indicated surface and near-surface velocities that were thermodynamically and dynamically incompatible with an active convective system coupled to a mid-level trough. Without applying dynamic profile compensations to account for localized mesoscale boundary layer currents, such as the sea-breeze front and a fast-moving storm-scale gust front, the bulk shear and storm-relative helicity values remain insufficient to explain mesocyclonic rotation. The adjusted operational profile indicates moderate storm-relative helicity within the lowest kilometer, suggesting that localized directional wind shear was sufficient to sustain a transient rotating updraft.

This reliance on uncompensated numerical models explains the analytical gaps in early exploratory papers (Santos, 2025a, 2025b). The earliest investigation restricted its scope to surface wind convergence, overlooking mid- and upper-level synoptic forcing, which resulted in an incomplete rendering of the supercell's vertical mechanics. Subsequent revisions introduced three-dimensional georeferencing but misclassified peripheral cloud features as multiple vortices. These compounding interpretative errors highlight the necessity of an integrated forensic approach. Relying exclusively on remote sensing or visual records without combining them with

high-resolution mesoscale reanalysis and direct botanical damage surveys increases the margin of error in intensity classifications.

The instrument data gaps surrounding this event underscore the limitations of regional severe weather monitoring networks. Local radar systems lacked the spatial and temporal resolution required to capture compact, low-level rotational signatures, while the surface station network was too sparse to capture the sharp pressure deficits or wind shifts associated with a narrow vortex path. Consequently, the storm appeared on instruments as an ordinary convective cell, facilitating conservative interpretations that overlooked the tornadic event.

This structural under-reporting stems from a broader systemic tendency to ignore rotating storms that develop outside classic, highly unstable synoptic environments. To address these intermediate convective profiles, Piracicaba Meteorológica (2025) utilizes an internal classification framework that establishes a clear operational distinction between mini-supercells, low-topped supercells, and marginal supercells. Under this framework, mini-supercells possess the complete, balanced structural configuration of a classic supercell, including an organized mesocyclone, but are scaled down horizontally. Low-topped supercells, by contrast, are dynamically limited by lower equilibrium levels and lower anvils, occurring under moderate instability but intense shallow shear. Both categories are differentiated from marginal supercells, which exhibit weaker internal rotation and depend almost entirely on localized baroclinic boundaries to focus vorticity. The documentation of the January 2025 event demonstrates that sub-classical systems can generate low-tier tornadoes. Relying on rigid, classic forecasting templates where radar and synoptic metrics must meet extreme criteria risks misclassifying narrow, short-lived tornadoes as straight-line winds or ordinary convective turbulence.

Conclusion

The integrated analysis conducted in this study substantiates that the meteorological event recorded in Piracicaba on January 31, 2025, was a tornado generated by a marginal supercell that impacted a commercial eucalyptus plantation and the Jacob Canale Municipal Road within the Campestre neighborhood. The three-dimensional geometric reconstruction derived from amateur video footage successfully mapped the spatial orientation and physical dimensions of the tornadic funnel, while the synoptic and mesoscale reanalysis identified an atmospheric profile that was marginally supportive of localized, rotating deep convection.

The retroactive forensic field investigation executed in 2026 provided critical empirical evidence of severe wind-induced damage along the estimated convective path. The documented structural failures, including the permanent trunk torsion in juvenile trees, and widespread aerodynamic defoliation, lodging, and complete main stem splitting across the commercial eucalyptus stand, spatially align with the photogrammetrically modeled translation vector.

Based on the synthesis of this biophysical evidence, the severity of the event significantly exceeds the preliminary F0 rating proposed by exploratory assessments in 2025. The observed structural failures match the damage indicators established for the EF1 category on the Enhanced Fujita Scale, which is characterized by wind speeds capable of inducing clean mechanical fractures in healthy timber and moderate canopy destruction. Conversely, while specific localized damage patterns matched the EF2 damage indicators, structural uncertainties and a lack of broader corroborating indicators prevent a definitive upgrade to that intensity level. Furthermore, due to the relocation of the research infrastructure from Piracicaba, Brazil, to St. Marys, Canada, the intensity classification methodology was transitioned to seamlessly integrate

the standardized United States Enhanced Fujita framework damage indicators alongside Canadian operational protocols regarding the volume of affected arboreal masses.

In addition to the intensity reassessment, this investigation clarifies that the visual features captured in the photographic record do not represent isolated, non-tornadic scud formations. Instead, they constitute a legitimate tornadic funnel partially enveloped by highly saturated, turbulent peripheral condensation beneath the low-topped storm base. Consequently, the Piracicaba tornado of January 31, 2025, is best classified as a short-lived, small-scale EF1 tornadic event associated with a marginal supercell.

References

Branick, M. (1996). A comprehensive glossary of weather terms for storm spotters. *NOAA Technical Memorandum NWS SR-145*.

Davies-Jones, R., Trapp, R. J., & Bluestein, B. H. (2001). Tornadoes and tornadic storms. *Meteorological Monographs, 50,* 167–222. https://doi.org/10.1175/0065-9401-28.50.167

Doswell, C. A., III, & Burgess, D. W. (1993). Tornadoes and tornadic storms: A review of conceptual models. In C. Church, J. Galway, R. Davies-Jones, & G. Darkow (Eds.), *The tornado: Its structure, dynamics, prediction, and hazards* (Vol. 79, pp. 161-172). American Geophysical Union. https://doi.org/10.1029/GM079p0161

Environment Canada. (2013). *Canadian Enhanced Fujita Scale (EF-Scale) Technical Documentation: Damage Indicators and Degrees of Damage*. Environment Canada.

Gliksman, D., Averbeck, P., Becker, N., Gardiner, B., Goldberg, V., Grieger, J., Handorf, D., Haustein, K., Karwat, A., Knutzen, F., Lentink, H. S., Lorenz, R., Niermann, D., Pinto, J. G., Queck, R., Ziemann, A., & Franzke, C. L. E. (2023). A European perspective on wind and storm damage – from the meteorological background to index-based approaches to assess impacts. *Natural Hazards and Earth System Sciences*, *23*(6), 2171–2201. https://doi.org/10.5194/nhess-23-2171-2023

Google (2025). [Snapping and growth stress in eucalyptus plantation along the Jacob Canale Road]. *Google Maps*. https://www.google.com/maps/@-22.7641887,-47.6871989,3a,53.6y,196.66h,93.75t/

Google (2025). [Decapped eucalyptus tree between the newly constructed roads and the Jacob Canale Road]. *Google Maps*. https://www.google.com/maps/@-22.7642417,-47.6876208,3a,37.6y,200.38h,105.87t/

Lima, C. A. G., & Selani, R. L. (2008). Tornados: uma nova realidade no Brasil? In *Anais do Congresso de Iniciação Científica das Faculdades Integradas de Ourinhos*. Faculdades Integradas de Ourinhos. http://cic.fio.edu.br/anaisCIC/anais2008/Artigos/Geografia/011-TORNAD.pdf

Lopes, M. M., & Nascimento, E. de L. (2025). Climatologia de ocorrências tornádicas no Sul do Brasil. *Ciência e Natura*, *47*(esp. 3), Artigo e84051. https://doi.org/10.5902/2179460X84051

Markowski, Paul, & Richardson, Yvette. (2010). *Mesoscale meteorology in midlatitudes*. Wiley-Blackwell. https://doi.org/10.1002/9780470682104

Mostafiz, R. B., Rohli, R. V., Friedland, C. J., Gall, M., & Bushra, N. (2022). Future crop risk estimation due to drought, extreme temperature, hail, lightning, and tornado at the census tract level in Louisiana. *Frontiers in Environmental Science, 10*, Artigo 919782. https://doi.org/10.3389/fenvs.2022.919782

Piracicaba Meteorológica. *Supercell database for the Piracicaba climatic region*. Retrieved June 20, 2025. https://doi.org/10.3389/fenvs.2022.919782

Ribeiro, B., Schild, G., Santos, L., Nascimento, E. L., Lopes, M., Goede, V., dos Santos, L. O., Costa, I., Ferreira, V., Oliveira, M., Telles, J., & Furlan, L. (2022). *The Brazilian severe storm reports database: methodology and a preliminary climatology* [Poster presentation]. Severe Local Storms Conference.

Rodrigues, R. R. (1999). *A vegetação de Piracicaba e municípios do entorno* (Circular Técnica IPEF nº 189). Instituto de Pesquisas e Estudos Florestais. https://www.ipef.br/publicacoes/ctecnica/nr189.pdf

Santos, E. K. dos. (2025a). *Avaliação georreferenciada e modelagem da trajetória do tornado em Piracicaba no final de janeiro de 2025*. Piracicaba Meteorológica, 3.

Santos, E. K. dos. (2025b). *Discussão sobre a ocorrência de um tornado em Piracicaba em janeiro de 2025*. Piracicaba Meteorológica, 3.

Smith, R. K., & Leslie, L. M. (1979). A numerical study of tornadogenesis in a rotating thunderstorm. *Quarterly Journal of the Royal Meteorological Society*, *105*(443), 107–127. https://doi.org/10.1256/smsqj.44307

Teramoto, E. R., Lepsch, I. F., & Vidal-Torrado, P. (2001). Relações solo, superfície geomórfica e substrato geológico na microbacia do ribeirão Marins (Piracicaba - SP). *Scientia Agricola*, *58*(2), 361–371. https://doi.org/10.1590/S0103-90162001000200021

Texas Tech University, Wind Science and Engineering Research Center. (2006). *Enhanced Fujita Scale (EF Scale) development* (WERC Report). Texas Tech University.

Thompson, R. L., Edwards, R., Hart, J. A., Elmore, K. L., & Markowski, P. (2003). Close proximity soundings within supercell environments obtained from the Rapid Update Cycle. *Weather and Forecasting*, *18*(6), 1243–1261. https://doi.org/10.1175/1520-0434(2003)018<1243:CPSWSE>2.0.CO;2

Wollmann, C. A., & Iensse, A. C. (2019). A gênese climática dos tornados nos estados da Região Sul do Brasil e São Paulo. *Geo UERJ*, (34), Artigo e40941. https://doi.org/10.12957/geouerj.2019.40941

Zipser, E. J., Cecil, Daniel J., Liu, Chuntao, Nesbitt, Stephen W., & Yorty, David P. (2006). Where are the most intense thunderstorms on Earth? *Bulletin of the American Meteorological Society*, *87*(8), 1057-1071. https://doi.org/10.1175/BAMS-87-8-1057